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13. ABSTRACT (Maximum 200 words)

Research was continued in two different areas – fast algorithms exploiting displacement structure and state-space estimation and adaptive filtering. In the first, the theory has been successfully extended to current problems in numerical linear algebra. These generally involve Vandermonde-and Cauchy-like matrices, as encountered frequently for example in polynomial and rational interpolation problems and in the recent fast multipole methods of V. Rokhlin. In contrast, control and signal processing problems involve Toeplitz- and Hankel-like matrices.

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Studies in Estimation Theory, Applications and Implementation

Final Report

by

Professor Thomas Kailath and Professor Arogyaswami Paulraj
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February 1993 - October 31, 1995

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FINAL REPORT

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9. **Awards and Honors during this period:** See Attached.
10. **Scientific Personnel Supported by this Project and Degrees Awarded During This Reporting Period:**

Principal Investigators:	Professor Thomas Kailath
	Professor Arogyaswami Paulraj
Postdoctoral Scholars:	Dr. M. Viberg
	Dr. K. Giridar
	Dr. V. Olshevsky
Graduate Students:	Mr. T. Boros
	Mr. B. Halder
	Mr. A. Naguib

Advanced Degrees

a. A. Naguib, *Adaptive Antennas in CDMA Wireless Communications*, Ph.D., Stanford University, Nov. 1995.

b. T. Boros, *A Displacement Structure Approach To Unconstrained Rational Interpolation*, Ph.D., Stanford University, Oral defense completed, Now employed by Watkins Johnson. Expects to submit a thesis in June 1996.

11. **Report of Inventions (By Title Only):** N/A

SIGNIFICANT ACHIEVEMENTS

1. Displacement Structure in Control and Signal Processing

This is a topic largely developed with Army support, beginning in 1976. The topic has grown rapidly in recent years. A 90-page survey paper appeared in SIAM Review, Sep. 1995. Two specialized international conferences are planned on the topic - one at UC Santa Barbara Aug. 1-3, 1996 and the other at Contona, Italy, Sep. 8-14, 1996.

The papers on this topic appearing in the reporting period are [J5]-[J7], [J11] [J14]-[J17], [J19], [J23], [J27]-[J28], [J30]-[J31], [J33].

Especially notable in the last year was extension of the theory to important classic problems in control theory.

- stability theory [J5, J26]
- the partial realization problem [J17, A1]
- the four-block problem of $\mathcal{H}_\infty$ theory [J19]

A new direction was extension of the theory to problems in numerical linear algebra. These generally involve Vandermonde- and Cauchy-like matrices (as encountered for example in polynomial and rational interpretation problems). In contrast, control and signal processing problems involve Toeplitz- and Hankel-like matrices. As can be seen from the list of publications, these papers appear in a different set of journals (Math. Comp.; Integ. Eqns and Oper. Thy; SIAM J. Matrix Anal.; Lin. Alg. and Appl.; Numerische Math.). The relevant citations are [J30, J31] and [R2]-[R9].

2. State-space Theory

We have returned to this area after several years. One motivation was our discovery that state-space formulation could dramatically simplify and extend the literature on *Adaptive Filtering.* This has been a burgeoning topic in recent years, as technology advances have made more feasible the implementation of various algorithms. However the field has been developed mostly in the signal processing community. Several textbooks exist, esp. Widrow and Stearns ("Adaptive Signal Processing," Prentice Hall, 1985) and Haykin ("Adaptive Filter Theory," Prentice Hall, 2nd ed., 1991.) Our results were published as a survey paper [J33]. This paper has led Haykin to extensively revise his textbook for a 3rd edition which should appear later in 1996. In fact, Haykin (we were told) successfully nominated our paper for the 1995 D. G. Fink Prize Award of the IEEE for "an outstanding review tutorial/survey paper in any 1994 IEEE publication."

Adaptive filtering problems involve both updating (addition of data) and downdating (deleting of data). In control, we generally only talk about updating, but signal processing allows both (*e.g.* in the so-called "sliding window" schemes).

We found that the way to handle this theory is by introducing "random variables" with negative variances. This is impossible in the usual Hilbert space theory, but can be accommodated by going to indefinite metric spaces (and to Krein spaces, in particular). This recognition led us to reexamine the literature on $\mathcal{H}_\infty$ theory, which is in many ways a generalization of game theory, where we have an indefinite objective function. This has been a very fruitful thought, leading to a considerable body of work. The first two parts appear as two long papers [J34, J35]. The main point is that 40 years of work on the Hilbert-space based Kalman filter theory can now be adapted to the relatively new $\mathcal{H}_\infty$ theory. For example, this point of view has guided us to the first square-root and Chandrasekhar $\mathcal{H}_\infty$ filters, and to new asymptotic results for $\mathcal{H}_\infty$ problems.

3. Array Signal Processing

A number of publications based on work largely done in earlier periods appeared: papers [J1, J8, J9, J12, J18, J21, J24, J25].

4. Communications

A new area of research, which has spanned about 50 papers by several others including my former students G. Xu and L. Tong, was initialed by the paper [J13] on a method for communication channel identification using second-order statistics. This had been thought to be impossible because such statistics are insensitive to phase. L. Tong's crucial insight was that this phase insensitivity was only true for (wide-sense) stationary second-order statistics. However by oversampling the received signal, we can get nonstationary (actually cyclostationary) second-order statistics and phase information can be recovered from these statistics.

5. Smart Antennas

We have obtained important results on the use of array processing techniques, (many of them developed in our earlier ARO/ONR/SDI projects), to improve wireless (cellular) communications, esp. with the CDMA (code-division-multiple-access, using spread-spectrum signals) digital technology. Papers in this area are [J20, J22] and several conference papers, [C1]-[C10].

We developed a space-time processing framework for the array vector response estimation and derived the corresponding optimum beamformer. In our approach we esti-

mate the array response vector based on temporal structure (code filtering) and decision directed processing. Further we have carried out extensive simulations to model performance in networks incorporating spatial processing and established that significant improvements in system capacity are possible.

A major advantage of spread-spectrum communication systems is their ability to exploit the multipath structure of the received signal. A standard RAKE receiver estimates the path delays and amplitudes and coherently combines different path signals to mitigate the effects of multipath. We propose an improved RAKE receiver that exploits the spatial properties of the multipath environment. We estimate the spatial channel for each path and then use it in a multichannel RAKE receiver which performs as a time and space matched filter. We have shown that a multichannel RAKE can increase signal to interference ratio in CDMA cellular networks and thereby improve performance.

The payoff of such research can be significant improvement in multiple access communications systems both for military and civilian applications. Our work in this area has excited significant interest.

ARO SUPPORTED PUBLICATIONS

Grant Number: DAAH04-93-G-0029
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Journal Papers

[J1] A. L. Swindlehurst and T. Kailath, "Azimuth/elevation Direction Finding Using Regular Array Geometries," *IEEE Trans. Aero. Elec. Systems*, 29(1):145-156, Jan. 1993.

[J2] D. Pal, "Gohberg-Semencul Type Formulas via Embedding of Lyapunov Equations," *IEEE Trans. Signal Processing*, 41(6):2208-2215, Jun. 1993.

[J3] T. Varvarigou, V. Roychowdhury, and T. Kailath. "Reconfiguring Processor Arrays Using Multiple-Track Models," *IEEE Trans. Communications*, 44(11):1281-1293, Nov. 1993.

[J4] A. L. Swindlehurst and T. Kailath, "A Performance Analysis of Subspace-based Methods in the Presence of Model Error. II. Multidimensional Algorithms," *IEEE Trans. Signal Processing*, 41(9):2882-2890, Sep. 1993.

[J5] D. Pal and T. Kailath, "Displacement Structure Approach to Singular Root Distribution Problems: The Unit Circle Case," *IEEE Trans. Automatic Control*, 39(1):238-245, Jan. 1994.

[J6] R. Ackner, H. Lev-Ari, and T. Kailath, "The Schur Algorithm for Matrix-Valued Meromorphic Functions," *SIAM J. Matrix Anal. Appl.*, 15(1):140-150, Jan. 1994.

[J7] T. Kailath and J. Chun, "Generalized Displacement Structure for Block-Toeplitz, Toeplitz-Block, and Toeplitz-Derived Matrices," *SIAM J. Matrix Anal. Appl.*, 15(1):114-128, Jan. 1994.

[J8] G. Xu, R. Roy, T. Kailath, "Detection of Number of Sources via Exploitation of Centro-Symmetry Property," *IEEE Trans. Signal Processing*, 42(1):102-112, Jan. 1994.

[J9] G. Xu, S.D. Silverstein, R.H. Roy, and T. Kailath, "Beamspace ESPRIT," *IEEE Trans. Signal Processing*, 42(2):349-356, Feb. 1994.

[J10] M. Genossar, H. Lev-Ari, and T. Kailath, "Consistent Estimation of Cyclic Autocorrelation," *IEEE Trans. Signal Processing*, 42(3):595-603, March 1994.

[J11] A. Sayed and T. Kailath, "Extended Chandrasekhar Recursions," *IEEE Trans. Automatic Control*, 39(3):619-623, March 1994.

[J12] G. Xu and T. Kailath, "Fast Subspace Decomposition," *IEEE Trans. Signal Processing*, 42(3):539-551, March 1994.

[J13] L. Tong, G. Xu, and T. Kailath, "Blind Identification and Equalization Based on Second-Order Statistics: A Time Domain Approach," *IEEE Tran. Inform. Thy.*, 40(2):340-349, March 1994.

[J14] D. Pal and T. Kailath, "Fast Triangular Factorization and Inversion of Hankel and Related Matrices With Arbitrary Rank Profile," *SIAM J. Matrix Anal. Appl.*, 15(2):451-478, April 1994.

[J15] A. Sayed, H. Lev-Ari, and T. Kailath, "Time-Variant Displacement Structure and Triangular Arrays," *IEEE Trans. Signal Processing*, 42(5):1052-1062, May 1994.

[J16] A. Sayed, T. Constantinescu, and T. Kailath, "Time-Variant Displacement Structure and Interpolation Problems," *IEEE Trans. Automatic Control*, 39(5):960-976, May 1994.

[J17] T. Boros, A. Sayed, and T. Kailath, "Structured Matrices and Unconstrained Rational Interpolation Problems," *Linear Algebra Appl.*, 203-204:155-188, June 1994.

[J18] G. Xu and T. Kailath, "Fast Estimation of Principal Eigenspace Using Lanczos Algorithm," *SIAM J. Matrix Anal. Appl.*, 15(3):974-994, July 1994.

[J19] T. Constantinescu, A.H. Sayed and T. Kailath, "A Recursive Schur Based Approach to the Four-Block Problem," *IEEE Trans. Automatic Control*, 39(7):1476-1481, July 1994.

[J20] A. Naguib, A. Paulraj and T. Kailath, "Capacity Improvement with Base-Station Antenna Arrays in Cellular CDMA," *IEEE Trans. Vehicular Technology*, 43(3):691-698, August 1994.

[J21] G. Xu, H. Zha, G. Golub and T. Kailath, "Fast Algorithms for Updating Signal Subspaces," *IEEE Trans. Circuits & Systems*, 41(8):537-549, August 1994.

[J22] D. Gerlach and A. Paulraj, "Adaptive Transmitting Antenna Arrays with Feedback," *IEEE Signal Processing Letters*, 10(1):150-152, October 1994.

[J23] A. Sayed and T. Kailath. "A State-Space Approach to Adaptive RLS Filtering," *IEEE ASSP Magazine*, 11(3):18-60, July 1994.

[J24] M. Viberg and A. Swindlehurst. "Analysis of the Combined Effects of Finite Samples and Model Errors on Array Processing Performance," *IEEE Trans. Signal Processing*, 42:3073-3083, Nov. 1994.

[J25] M. Viberg and A. Swindlehurst. "A Bayesian Approach to Auto-Calibration for Parametric Array Signal Processing," *IEEE Trans. Signal Processing*, 42:3495-3507, Dec. 1994.

[J26] M. Genossar, H. Lev-Ari, and T. Kailath. "Consistent Estimation of Cyclic Autocorrelation," *IEEE Trans. Signal Processing*, 42(3):595-603, March 1994.

[J27] A. Sayed, H. Lev-Ari, and T. Kailath. "Time-Variant Displacement Structure and Triangular Arrays," *IEEE Trans. Signal Processing*, 42(5):1052-1062, May 1994.

[J28] D. Pal and T. Kailath. "Displacement Structure Approach to Singular Root Distribution Problems: The Imaginary Axis Case," *IEEE Trans. Circuits and Systems I: Fundamental Theory and Applications*, 41(2):138-148, Feb. 1994.

[J29] T. Kailath, "Encounters with the Berlekamp-Massey Algorithm," *Communications and Cryptography: Two Sides of One Tapestry*, Kluwer Publishers, pp.209-225, 1994.

[J30] I.Gohberg, T. Kailath, and V. Olshevsky, "Fast Gaussian elimination with partial pivoting for matrices with displacement structure", *Math. of Computation*, 64:1557-1576, Oct. 1995.

[J31] T. Kailath, and V. Olshevsky, " Displacement structure approach to Chebyshev–Vandermonde and related matrices," *Integral Equations and Operator Theory*, 22:65-92, 1995.

[J32] M. Viberg, P. Stoica, and B. Ottersten. "Array Processing in Correlated Noise Fields Based on Instrumental Variables and Subspace Fitting," *IEEE Trans. Signal Processing*, 43:1187-1199, May 1995.

[J33] A. Sayed and T. Kailath, "Displacement Structure: Theory and Applications," *SIAM Review,* 37(3):297-386, Sep. 1995.

[J34] B. Hassibi, A. Sayed and T. Kailath, "Linear Estimation in Krein Spaces – Part I: Theory," *IEEE Trans. Automatic Control,* AC-41:18-33, Jan. 1996.

[J35] B. Hassibi, A. Sayed and T. Kailath, "Linear Estimation in Krein Spaces – Part II: Applications," *IEEE Trans. Automatic Control,* AC-41:34-49, Jan. 1996.

Papers Accepted for Publication

[A1] B. Hassibi, A. Sayed, and T. Kailath, "H^∞ Optimality of the LMS Algorithm," *IEEE Trans. Signal Processing*, Feb. 1996.

[A2] T. Boros, A. Sayed and T. Kailath, "A Recursive Method for Solving Unconstrained Tangential Interpolation Problems," *IEEE Trans. Automatic Control.*

Papers Under Review

[R1] D. Gerlach and A. Paulraj, "Adaptive Transmitting Antenna Arrays With Feedback," *IEEE Trans. Vehicular Technology.*

[R2] T. Kailath and V. Olshevsky, "Displacement Structure Approach to Chebyshev-Vandermonde and Related Matrices," *J. Integral Equations and Operator Theory.*

[R3] T. Kailath and V. Olshevsky, "Displacement Structure Approach to Polynomial Vandermonde and Related Matrices," *Linear Algebra and Its Appl.*.

[R4] T. Boros, T. Kailath and V. Olshevsky, "Fast Algorithms for Solving Cauchy Linear Systems," *SIAM J. Matrix Anal. Appl.*

[R5] T. Boros, T. Kailath and V. Olshevsky, "Fast Algorithms for Solving Vandermonde and Chebyshev-Vandermonde Systems," *SIAM J. Matrix Anal. Appl.*

[R6] T. Boros, T. Kailath, and V. Olshevsky, "Error Analysis of a Fast Algorithm for Solving Cauchy Linear Systems," *SIAM J. Matrix Anal. Appl.*

[R7] T. Kailath, and V. Olshevsky, "Symmetric and Bunch-Kaufman Pivoting for Partially Structured Cauchy-like Matrices with Applications to Toeplitz-like Linear Equations," *SIAM J. Matrix Anal. Appl.*

[R8] I. Gohberg, and V. Olshevsky, "Fast Inversion of Vandermonde and Vandermonde-like Matrices," *SIAM J. Matrix Anal. Appl.*

[R9] T. Kailath, and V. Olshevsky, "The Fast Bjorck-Pereyra-type Algorithm for Parallel Solution of Cauchy Linear Systems," *Numerische Math.*

Conference Papers

[C1] A. Naguib, A. Paulraj, and T. Kailath. "Capacity Improvement of Base-Station Antenna Array Cellular CDMA," 1993 Asilomar Conference, Pacific Grove, CA, 1993.

[C2] B. Suard, A. Naguib, G. Xu, and A. Paulraj. "Performance of CDMA Mobile Communication Systems using Antenna Arrays," Int'l. Conf. on Acoustics, Speech, Signal Processing, Minneapolis, MN, April 1993.

[C3] A. Naguib, A. Paulraj, and T. Kailath, "Performance of CDMA Cellular Networks with Base-Station Antenna Arrays," *Proc. 1994 Int'l. Zurich Seminar on Digital Comm.*, Zurich, Switzerland, March 1994.

[C4] A. Naguib, B. Khalaj, A. Paulraj, and T. Kailath, "Adaptive Channel Equalization for TDMA Digital Cellular Communications using Antenna Arrays," *Proc. 1994 Int'l. Conf. on Acoustics, Speech, Signal Processing*, Adelaide, Australia, April 1994.

[C5] A. Naguib, A. Paulraj, and T. Kailath, "Performance of CDMA Cellular Networks with Base-Station Antenna Arrays: The Downlink," *Proc. 1994 Int'l. Comm. Conf.*, New Orleans, LA, May 1994.

[C6] A. Naguib, A. Paulraj and T. Kailath, "Effects of Multipath and Base-Station Antenna Arrays on Uplink Capacity of Cellular CDMA," *Proc. 1994 Int'l. Comm. Conf.*, New Orleans, LA, May 1994.

[C7] A. Naguib and A. Paulraj, "A Base-Station Antenna Array Receiver for Cellular *1994 Asilomar Conf. on Signals, Systems, Computers*, Pacific Grove, CA, Nov. 1994.

[C8] D. Gerlach and A. Paulraj, "Adaptive Transmitting Antenna Methods for Multipath Environments," *1994 IEEE Global Communications Conference*, San Francisco, CA, Nov. 1994.

[C9] A. Naguib and A. Paulraj, "Effects of Multipath and Base-Station Antenna Arrays on Uplink Capacity of Cellular CDMA," *1994 IEEE Global Communications Conference*, San Francisco, CA, Nov. 1994.

[C10] D. Gerlach and A. Paulraj, "Adaptive Transmitting Antenna Methods for Multipath Environments," *1994 IEEE Global Communications Conference*, San Francisco, CA, Nov. 1994.

AWARDS AND HONORS

Professor Thomas Kailath

- Elected to Membership in American Academy of Arts and Sciences, March 1994.
- 1994 Best Paper Award from IEEE Trans. Semiconductor Manufacturing

  Y. M. Cho and T. Kailath, "Model Identification in Rapid Thermal Processing Systems," *IEEE Trans. Semiconductor Manufacturing*, 6(3):233-245, August 1993.

- Outstanding Paper Award from IEEE Trans. Signal Processing (Awarded in April 1994).

  D. T. M. Slock and T. Kailath, "Numerically Stable Fast Transversal Filters for Recursive Least-Squares Adaptive Filtering," *IEEE Trans. Signal Processing*, 39(1):92-114, January 1991.

- Best Paper Award from the European Association for Signal Processing (Awarded in Sep. 1994).

  D. T. M. Slock and T. Kailath, "A Modular Prewindowing Framework for Covariance FTF RLS Algorithms," *Signal Processing*, 28(1):47-61, July 1992.

- 1995 IEEE Education Medal for "leadership in graduate engineering education through a classic textbook in linear systems and creative interdisciplinary research."
- 1995 D. G. Fink Prize Award from the IEEE for "an outstanding review tutorial/survey paper in any 1994 IEEE publication." The paper was:

  A. Sayed and T. Kailath. "A State-Space Approach to Adaptive RLS Filtering," *IEEE ASSP Magazine*, 11(3):18-60, July 1994.

Professor Arogyaswami Paulraj

- Gowri Memorial Gold Medal for Best Technical Paper, *J. of the IETE*, India.

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13. ABSTRACT (Maximum 200 words)

We consider the problem of extending the estimation of signal parameters via rotational invariance techniques (ESPRIT) algorithm for multiple source, cochannel direction finding to the two-dimensional case (e.g., azimuth and elevation angle estimation). Two algorithms are presented, one based on the optimal (minimum variance) subspace fitting formulation of ESPRIT, and the other based on an approximation to it. The algorithms are applicable to antenna arrays composed of identical subarrays displaced in two dimensions, such as uniform rectangular phased arrays. Simulation results illustrating the relative performance of the algorithms are also presented.

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13. ABSTRACT *(Maximum 200 words)*

***Abstract*—We present a new way of deriving Gohberg–Semencul type inversion formulas for Hermitian Toeplitz and quasi-Toeplitz matrices. Our approach is based on certain Σ-lossless embedding of Lyapunov equations. It has been shown that if a nonsingular matrix R has Toeplitz displacement inertia $\{p, q\}$ then R^{-1} does not have the same Toeplitz displacement inertia. However, a para-Hermitian conjugate R^{-1} (which is defined in Section I) of R^{-1} will have this property. We have also shown that the Gohberg–Semencul type inversion formulas can be formed directly in terms of certain parameters of the embedding.**

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13. ABSTRACT (Maximum 200 words)

This is the second of a two-part paper dealing with the performance of subspace-based algorithms for narrowband direction-of-arrival (DOA) estimation when the array manifold and noise covariance are not correctly modeled. In Part 1, the performance of the MUSIC algorithm was investigated. In Part 2, we extend this analysis to *multidimensional* (MD) subspace-based algorithms including deterministic (or conditional) maximum likelihood, MD-MUSIC, weighted subspace fitting (WSF), MODE, and ESPRIT. A general expression for the variance of the DOA estimates is derived, and, with appropriate choices for certain matrices in the expression, it can be applied to any of the above algorithms and to any of a wide variety of scenarios (*e.g.*, gain/phase errors, mutual coupling, sensor position errors, noise covariance mismodeling, *etc.*). The simplicity of the resulting expressions facilitates performance comparisons and the development of robust algorithms. In particular, optimally weighted subspace fitting algorithms are derived for special cases involving random errors to the array manifold and noise covariance. Additionally, and somewhat surprisingly, it is shown that one-dimensional MUSIC outperforms all of the above MD algorithms for angle independent random array perturbations. Several simulation examples are included to validate the analysis.

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Reconfiguring Processor Arrays Using Multiple-Track Models

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13. ABSTRACT *(Maximum 200 words)*

In this paper we present new results on systematic procedures for reconfiguring processor arrays in the presence of faulty processors. In particular, we consider models that use multiple tracks along every channel and a single spare row (or column) of Processing Elements (PEs) along each boundary of the array. In the presence of faulty PEs, the general methodology for reconfiguration involves replacing every faulty PE logically (rather than physically) by a spare PE through a sequence of logical substitutions; these sequences of substitutions are referred to as *compensation paths.* The determination of such compensation paths for every faulty PE has to be followed by an algorithm to connect each PE to its logical neighbors. It is easy to see that if the number of available routing tracks is fixed, then the compensation paths cannot be arbitrary. Hence, an important question to address is: how many tracks should one provide so as to allow a large enough class of compensation paths, and yet keep the hardware redundancy low. In this paper we show that if there exists a set of compensation paths subjected only to the constraints of continuity and nonintersection, then routing channels with *three tracks* are enough for the reconfiguration of the array. This theoretical result matches the empirical observations presented by several researchers showing that 3-track routing channels are sufficient for reconfiguring most instances. We refer to the underlying model as a *3-track-1-spare model*; this is done to facilitate distinguish it from other models that not only use multiple tracks but also multiple spare rows (or columns) along each boundary. We present an efficient algorithm for reconfiguration in our 3-track-1-spare model and evaluate its performance. Our experimental results show that it has much higher reconfiguration probability than other models that use considerably more spare processors.

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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13. ABSTRACT *(Maximum 200 words)*

***Abstract*—A general theory of tabular form root distribution procedures based on LDL^* factorization of Bezoutians is presented in this note. In particular, we concentrate on the singular cases arising in the Schur–Cohn test. A one-to-one correspondence is established between the rank profile of the underlying Bezoutians and the occurrence of the singular cases. Combining this interpretation with the newly developed factorization procedures of Pal and Kailath, it is possible to extend the new unified approach of Lev-Ari, Bistritz, and Kailath to the singular cases. By doing so, not only do we derive the well known Schur–Cohn procedure, but we also obtain new results. In fact, we are able to derive a new completely recursive procedure to deal with the "first kind of singularity."**

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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13. ABSTRACT *(Maximum 200 words)*

***Abstract*—The cyclic autocorrelation is often used to describe nonstationary random processes. In this paper we investigate the conditions under which the cyclic autocorrelation can be estimated consistently in mean square for discrete time Gaussian processes. We extend and generalize results of Hurd [17] and refine results of Boyles and Gardner [1]. We derive necessary and sufficient conditions for consistency in mean square of an estimator, which are in the form of a single sum of autocorrelation coefficients, in the form of a double sum of autocorrelation coefficients, in the bifrequency domain and in terms of the average spectrum. We also discuss the rate of convergence for this estimator.**

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Time-Variant Displacement Structure and Triangular Arrays

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13. ABSTRACT *(Maximum 200 words)*

***Abstract*— We extend the concept of displacement structure to time-variant matrices and use it to efficiently and recursively propagate the Cholesky factor of such matrices. A natural implementation of the algorithm is via a modular triangular array of processing elements. When the algorithm is applied to solve the normal equations that arise in adaptive least-squares filtering, we get the so-called QR algorithm, with the extra bonus of a parallelizable procedure for determining the weight vector. It is shown that the general algorithm can also be implemented in time-variant lattice form; a specialization of this result yields a time-variant Schur algorithm.**

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13. ABSTRACT *(Maximum 200 words)*

Adaptive filtering is gaining favor in numerous applications to help cope with time-variations of system parameters, and to compensate for the lack of *a priori* knowledge of the statistical properties of the input data. Over the last several years, a wide range of algorithms has been developed. These fall into four main groups: recursive least squares (RLS) algorithms and the corresponding fast versions; QR- and Inverse QR-least squares algorithms; least-squares lattice (LSL) and QR decomposition-based least squares lattice (QRD-LSL) algorithms; and gradient-based algorithms such as the least-mean square (LMS) algorithm.

It is practically impossible to list all the relevant references and all the major contributors to this field. However, the books [1]-[7], along with their extensive lists of references, should provide an excellent idea of the main results in this area. We shall, however, most often use the widely referenced textbook of Haykin [1] as a guide throughout our presentation.

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Analysis of the Combined Effects of Finite Samples and Model Errors on Array Processing Performance

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13. ABSTRACT *(Maximum 200 words)*

The principal sources of estimation error in sensor array signal processing applications are the finite sample effects of additive noise and imprecise models for the antenna array and spatial noise statistics. While the effects of these errors have been studied individually, their combined effect has not yet been rigorously analyzed. In this paper, we undertake such an analysis for the class of so-called *subspace fitting* algorithms. In addition to deriving first-order asymptotic expressions for the estimation error, we show that an overall optimal weighting exists for a particular array and noise covariance error model. In a companion paper, the optimally weighted subspace fitting method is shown to be asymptotically equivalent with the more complicated maximum *a posteriori* estimator. Thus, for the model in question, no other method can yield more accurate estimates for large samples and small model errors. Numerical examples and computer simulations are included to illustrate the obtained results and to verify the asymptotic analysis is realistic scenarios.

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13. ABSTRACT (Maximum 200 words)

A number of techniques for parametric (high-resolution) array signal processing have been proposed in the last few decades. These methods have been developed for many different applications, such as radar detection and underwater source localization. With few exceptions, such algorithms require an exact characterization of the array, including knowledge of the sensor positions, sensor gain/phase responses, mutual couplings, and receiver equipment effects. Unless all sensors are identical, this information must typically be obtained by experimental measurements (calibration). In practice, of course, all such information is inevitably subject to errors. Recently, several different methods have been proposed for alleviating the inherent sensitivity of parametric methods to such modeling errors. The technique proposed herein is related to the class of so-called procedures, but it is assumed that certain prior knowledge of the array response errors is available. This is a reasonable assumption in most applications, and it allows for more general perturbation models than does pure auto-calibration. The optimal maximum a posteriori (MAP) estimator for the problem at hand is formulated, and a computationally more attractive large-sample approximation is derived. The proposed technique is shown to be statistically efficient, and the achievable performance is illustrated by numerical evaluation and computer simulation.

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13. ABSTRACT *(Maximum 200 words)*

In 1969, J. Massey published a now-famous paper showing, among other things, that an iterative algorithm introduced by Berlekamp for decoding BCH codes also solved the problem of finding a shortest-length feedback shift register circuit for generating a given finite sequence of digits. This nice physical interpretation opened the door to connections with many other problems, including the minimal partial realization problems of linear system theory, Padé approximations and continued fractions, the fast algorithms of Levinson and Schur for Toeplitz matrices, inverse scattering, VLSI implementations, etc. This paper is an informal account of some of the different contexts in which the Berlekamp-Massey algorithm have been encountered in the work of the author and his students.

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13. ABSTRACT *(Maximum 200 words)*

Accurate signal parameter estimation from sensor array data is a problem which has received much attention in the last decade. A number of parametric estimation techniques have been proposed in the literature. In general, these methods require knowledge of the sensor-to-sensor correlation of the noise, which constitutes a significant drawback. This difficulty can be overcome only by introducing alternative assumptions that enable separating the signals from the noise. In some applications, the raw sensor outputs can be pre-processed so that the emitter signals are temporally correlated with correlation length longer than that of the noise. An *Instrumental Variable* (IV) approach can then be used for estimating the signal parameters without knowledge of the spatial color of the noise. A computationally simple IV approach has recently been proposed by the authors. Herein, a refined technique that can give significantly better performance is derived. A statistical analysis of the parameter estimates is performed, enabling optimal selection of certain user-specified quantities. A lower bound on the attainable error variance is also presented. The proposed optimal IV method is shown to attain the bound if the signals have a quasi-deterministic character.

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13. ABSTRACT *(Maximum 200 words)*

Abstract. In this survey paper, we describe how strands of work that are important in two different fields, matrix theory and complex function theory, have come together in some work on fast computational algorithms for matrices with what we call displacement structure. In particular, a fast triangularization procedure can be developed for such matrices, generalizing in a striking way an algorithm presented by Schur (1917) [*J. Reine Angew. Math.*, 147 (1917), pp. 205–232] in a paper on checking when a power series is bounded in the unit disc. This factorization algorithm has a surprisingly wide range of significant applications going far beyond numerical linear algebra. We mention, among others, inverse scattering, analytic and unconstrained rational interpolation theory, digital filter design, adaptive filtering, and state-space least-squares estimation.

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Fast Gaussian elimination with partial pivoting for matrices with displacement structure

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13. ABSTRACT *(Maximum 200 words)*

Fast $O(n^2)$ implementation of *Gaussian elimination with partial pivoting* is designed for matrices possessing certains kinds of *displacement structure*, including *Cauchy-like* matrices. We show how *Toeplitz-like*, *Toeplitz-plus-Hankel-like* and *Vandermonde-like* matrices can be transformed into Cauchy-like matrices by using Discrete Fourier, Cosine or Sine Transform matrices.

In particular this allows us to propose a new fast $O(n^2)$ Toeplitz solver GKO, which incorporates partial pivoting. A large set of numerical examples showed that GKO demonstrated stable numerical behavior and can be recommended for solving linear systems, especially with nonsymmetric, indefinite and ill-conditioned positive definite Toeplitz matrices. It is also useful for block Toeplitz and mosaic Toeplitz (Toeplitz-block) matrices.

The algorithms proposed in this paper suggest an alternative to a look-ahead approaches, where one have to jump over ill-conditioned leading submatrices, which in the worse case requires $O(n^3)$ operations.

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13. ABSTRACT *(Maximum 200 words)*

In this paper we use the displacement structure concept to introduce a new class of matrices, designated as *Chebyshev–Vandermonde-like* matrices, generalizing ordinary Chebyshev–Vandermonde matrices, studied earlier by different authors. Among other results the displacement structure approach allows us to give a nice explanation for the form of the Gohberg–Olshevsky formulas for the inverses of ordinary Chebyshev–Vandermonde matrices. Furthermore, the fact that the displacement structure is inherited by Schur complements leads to a fast $O(n^2)$ implementation of Gaussian elimination with *partial pivoting* for Chebyshev–Vandermonde–like matrices.

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***Abstract*—We show that several interesting problems in H^∞-filtering, quadratic game theory, and risk sensitive control and estimation follow as special cases of the Krein-space linear estimation theory developed in [1]. We show that all these problems can be cast into the problem of calculating the stationary point of certain second-order forms, and that by considering the appropriate state space models and error Gramians, we can use the Krein-space estimation theory to calculate the stationary points and study their properties. The approach discussed here allows for interesting generalizations, such as finite memory adaptive filtering with varying sliding patterns.**

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